HARBOR DEVELOPMENT STUDY

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CALIFORNIA INSTITUTE OF TECHNOLOGY

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The Cover

Storm waves attacking the shoreline at Redondo Beach, California. This is the type of physical environment where an artificial harbor might be constructed as an emergency measure. The harbor development study is aimed particularly at developing analytical design procedures for such harbors.

I. INTRODUCTION

A general objective of the Harbor Development study is the investigation of the wave energy distribution in harbor areas. Treated in a general way, the energy distribution in a harbor can be considered in two parts. The first concerns the amount and distribution of energy entering the harbor through the breakwater opening. Second is the consideration of the redistribution of energy by reflection and absorption at the harbor boundaries.

The first part, that of diffraction through breakwater openings, has been presented by this Laboratory in previous progress reports[1].

The second part, that of reflection and absorption at harbor boundaries, is the subject of this report. These factors are important in harbor design because the resultant wave pattern in a harbor is determined by both the incident and reflected waves.

In any harbor with reflecting boundaries the resultant wave pattern is usually complex and an exact solution by graphical or mathematical treatment would prove very difficult. However, an approximate graphical solution, developed recently by this Laboratory, appears promising.

This report presents the results of extensive measurements of wave disturbances in two idealized harbors and compares these results with those of the graphical analysis.

II. EXPERIMENTAL METHODS

A. Equipment and Techniques

Two general harbor shapes, built to a scale of 1/180, were tested; a rectangular harbor with prototype dimensions of 6000 ft x 4200 ft, and a square harbor, equal in area to the rectangular harbor, 5020 ft x 5020 ft. For both harbors the opening was 750 feet. Sixteen different conditions were tested with each harbor, combining the effects of four wave approach directions (90°, 60°, 45°, and 30°) and four beach conditions (no beach, 750-ft beach, 2250-ft beach, and 3750-ft beach). The beaches were centered in each case along the wall opposite the entrance and had slopes of 1 : 8. The harbors were formed by flanged sheet metal sections, 5 inches in height. Wave guides of the same height were installed between the harbor entrance and the wave machine to maintain the uniformity of the incident wave. While such a condition does not exist in the prototype it has been found that the diffraction phenomena at the harbor entrance are essentially unaffected.

Measurements of the incident waves and of the disturbance level within the harbors were made with electrical conductivity elements and recorded with the 17-channel oscillograph. This equipment has been fully described in the report on the Apra Harbor study[2]. Two elements were placed in the entrance channel to record incident wave height while 15 were arranged in an array (Fig.1) covering a prototype area of 215 ft x 405 ft at each of the test stations. It will be noted that the array, which formerly had its own supporting legs, has been combined with the calibrating device. This redesign by Lt.(jg) J.C. Hufft, including the addition of two level bubbles and a hook gage, greatly facilitates both the twice daily calibration of the elements and the placing of the array from position to position. The stations were located in the four corners of the harbors and at the quarter points of the side opposite the breakwater opening and the two sides at right angles to it, except that readings were taken only at the mid-points of these latter two sides in the case of the rectangular harbors. Further, in the case of harbors with beaches, the stations at the mid-point and quarter-points of the side opposite the opening were omitted where they would interfere with the beaches.

A general view of the basin, showing the rectangular harbor with 45° wave approach, the wave generator, the guide channel and the element array, is shown in Fig.2.

The imposed wave conditions throughout these tests were held constant with a wave height of eight feet and period of 10 seconds. The corresponding wave length in the prototype water depth of 60 feet is 385 feet. It is thus seen that the harbor opening is very nearly two wave lengths in width as is the shortest beach, with the intermediate length beach being six, and the longest beach ten wave lengths in width.

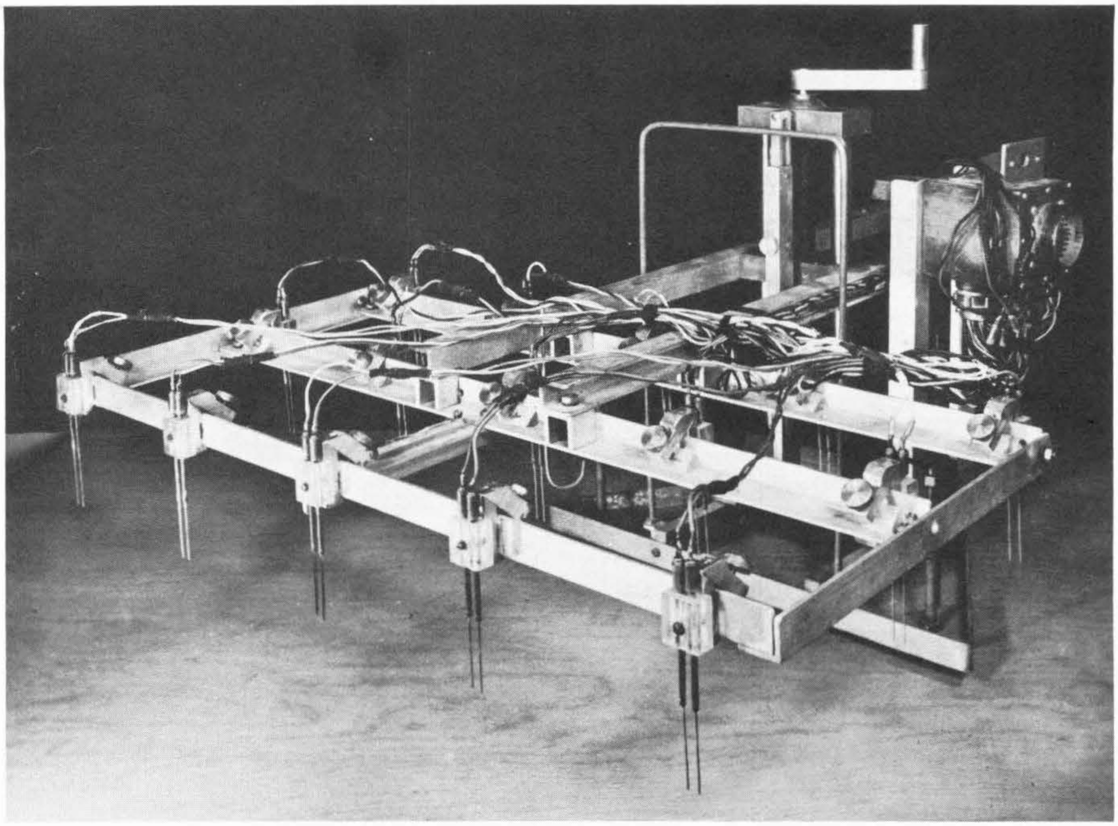


Fig. 1 - Modified Wave Height Element Array

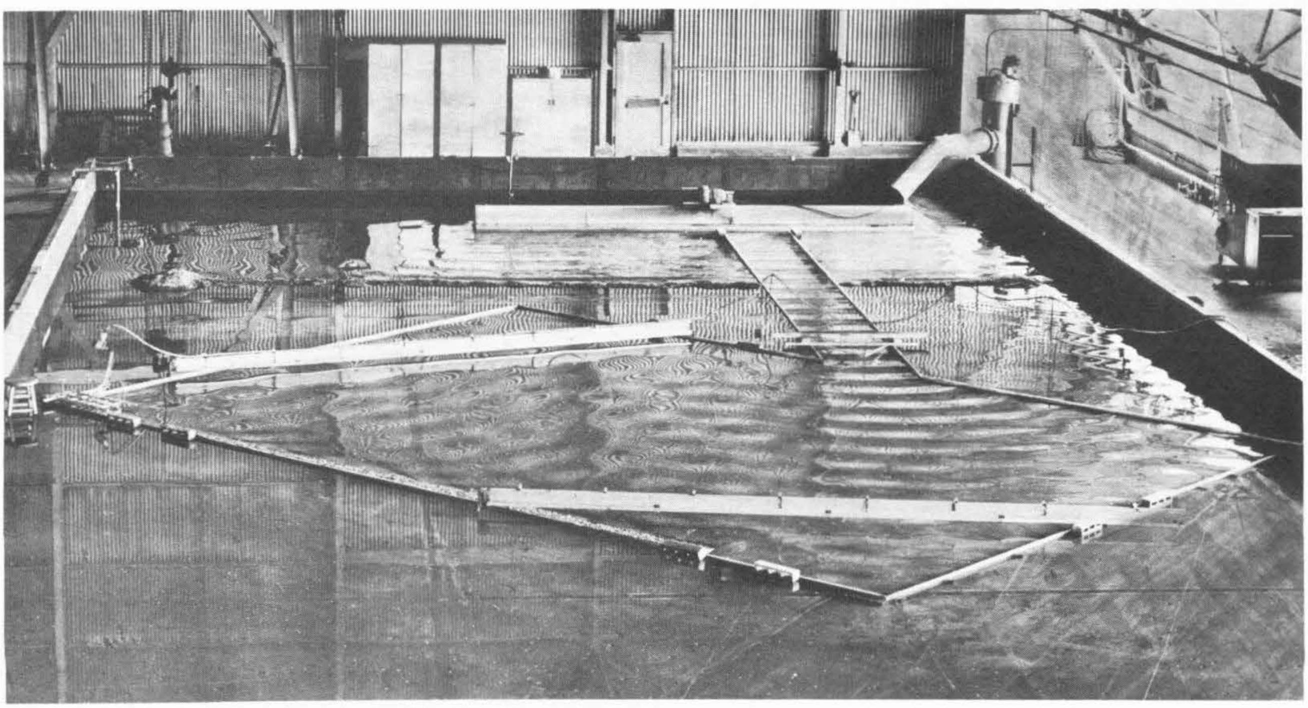


Fig. 2 - Laboratory Arrangement for Harbor Reflection Studies

B. Experimental Results and Conclusions

In Figs.3 and 4 are shown the effects of varying wave approach and varying length of absorbing beaches on the level of peripheral wave disturbance for the square and rectangular harbors. The values shown represent the "significant wave height". Only the average of the heights of the highest one-third of all waves measured is generally considered to be significant and this system was therefore employed. The runs at all stations were made in triplicate and the readings for the three runs for each element were then averaged. The highest five of the 15 averages were averaged again and this final value is considered to be representative of the disturbance for the entire test area.

The values thus obtained for each test station are shown on Figs.3 and 4 as percentages of the imposed wave height. The imposed wave heights were obtained by averaging the recordings of the two elements outside the harbor obtained throughout each day's runs.

A study of Figs.3 and 4 shows at once that the disturbances are highest in the direction of wave approach as is to be expected. It must be borne in mind that the beaches are centered along the side opposite the opening and are therefore across the direction of wave approach only in the case of the 90° approach and have a maximum attenuating effect only for this condition.

This accounts for the relatively small reduction in the general disturbance level in the cases of the other three directions of ap-

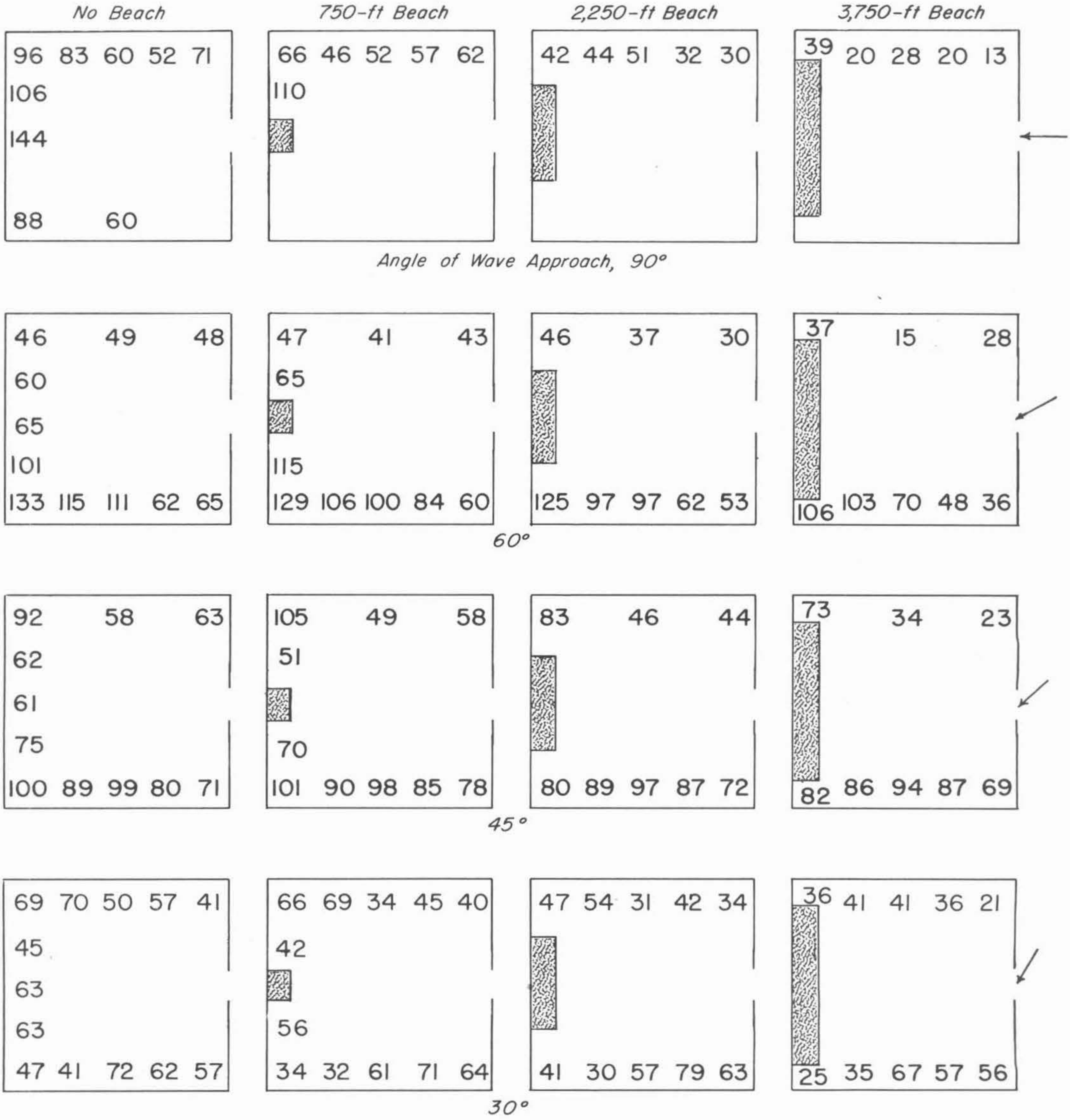


Fig. 3 - Measured Disturbance Factors for Square Harbors
Numbers refer to measuring areas as defined in the text

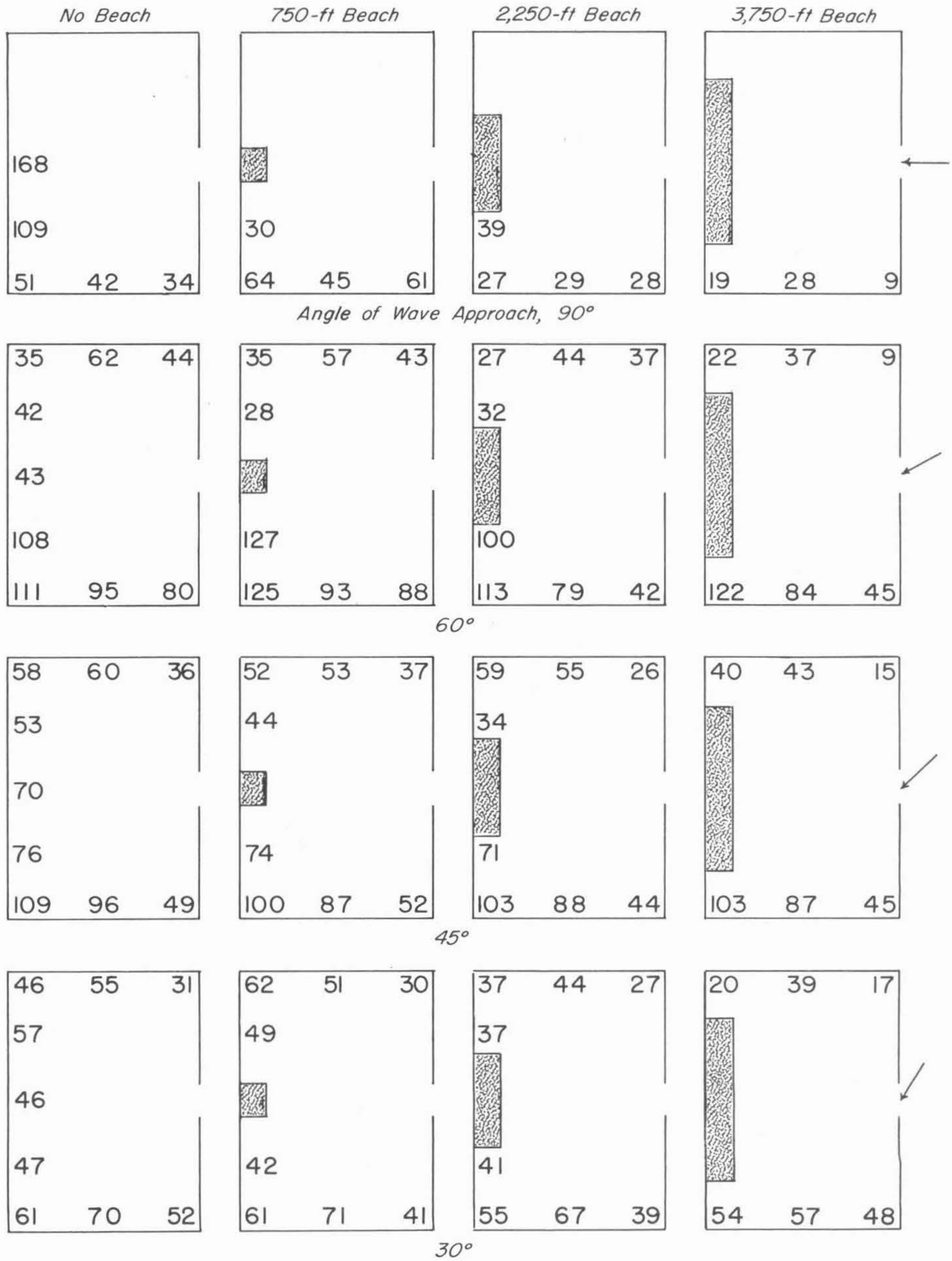


Fig. 4 - Measured Disturbance Factors for Rectangular Harbors
Numbers refer to measuring areas as defined in the text

proach. As used here the term "general disturbance level" applies only to the areas along the boundaries of the harbor and not to the central area, since no measurements were taken in the center. With a 90° approach and the 3750-ft beach the reduction for both the square and rectangular harbors amounts to 67% and 56% respectively of the disturbance without any beach, while the average reduction is only 29% for the other three approach angles. In addition, it may be noted that the 750-ft beach contributes hardly at all to a decrease in general disturbance level. This indicates again, that for maximum effectiveness beaches should be located normal to the main direction of wave propagation and should be as long as possible.

In general it might be expected that the disturbances in the entire area of the harbor should decrease with a decrease in approach angle of the waves, since the amount of energy admitted is reduced for oblique wave approach. This, however, does not appear to be true when only the peripheral areas are considered. With the exception of the square harbor without any beach, the peripheral disturbances in the other seven harbor configurations increase as the approach angle is shifted from 90° to 60° and 45°, and in the case of the 2250-ft and 3750-ft beaches also to 30°. This observation is an illuminating illustration of the importance of the reflection process. It is probable that this condition would be radically changed by shifting the beaches so that the line of propagation of wave fronts would be normal to them.

When the disturbance levels of the rectangular and square harbors with a given approach and beach condition and containing equal areas are compared, it is found that in general the peripheral disturbances are smaller in the rectangular harbor than in the square harbor. This is due to the fact that the energy contained in any segment of the wave crest decreases more rapidly from the center to the sides of the diffracted crest than it does from wave length to wave length. It follows, therefore, that the peripheral disturbances will be high for a rectangular harbor with the opening in the short side.

It will be noted on Figs.3 and 4 that in the case of 90° wave approach, disturbance values are shown only for one-half of each harbor. Observations in the 90° case were made only for one-half because the disturbance pattern should be symmetrical with a 90° approach. However, it must be stated that for the experiments this is not entirely so as can be seen in the delineation of the square harbor without beach, where in symmetric corners readings of 88 and 96 per cent of the imposed wave height were obtained. This, of course, is due to experimental error. On the other hand, at the mid-points of the two opposite sides, identical wave heights were observed. Attention should also be called to the relatively high disturbances adjacent to the ends of the beaches. It is felt that these high readings are due to the shape of the beaches used. While the slope, normal to the wall, was 1 : 8, the ends of the beach dropped off vertically which permitted the production of local standing waves between beach ends and side walls. Such a condition would most likely not exist in an actual installation and in the future laboratory tests will be made with the beaches sloping also toward the sides.

III. AN APPROXIMATE GRAPHICAL SOLUTION

A. Theory

The wave energy entering a harbor through a breakwater opening distributes itself inside the harbor according to certain natural laws. In an extremely large harbor with constant depth and with no currents, the distribution could be determined directly using the Morse-Rubenstein theory. In this extremely large harbor the waves would diminish with distance according to the inverse square law until they were undistinguishable without hitting any harbor boundaries, and therefore no reflections would occur. The lack of current and the constant depth would preclude any refraction. Therefore, the Morse-Rubenstein theory would allow a direct determination.

Distribution data based on the Morse-Rubenstein theory have been determined by the National Bureau of Standards at the request of this Laboratory and the data have been checked experimentally(1). Polar plot of intensity factors based on this theory are shown in Fig.5. The plots may be used to determine the ratio of wave height passing any location inside the harbor to the wave height incident at the breakwater.

In almost all harbors, however, the harbor dimensions are small enough that reflections take place, and must be considered. The approximate graphical method takes reflections into account, but does not consider refraction effects due to depth changes or currents.

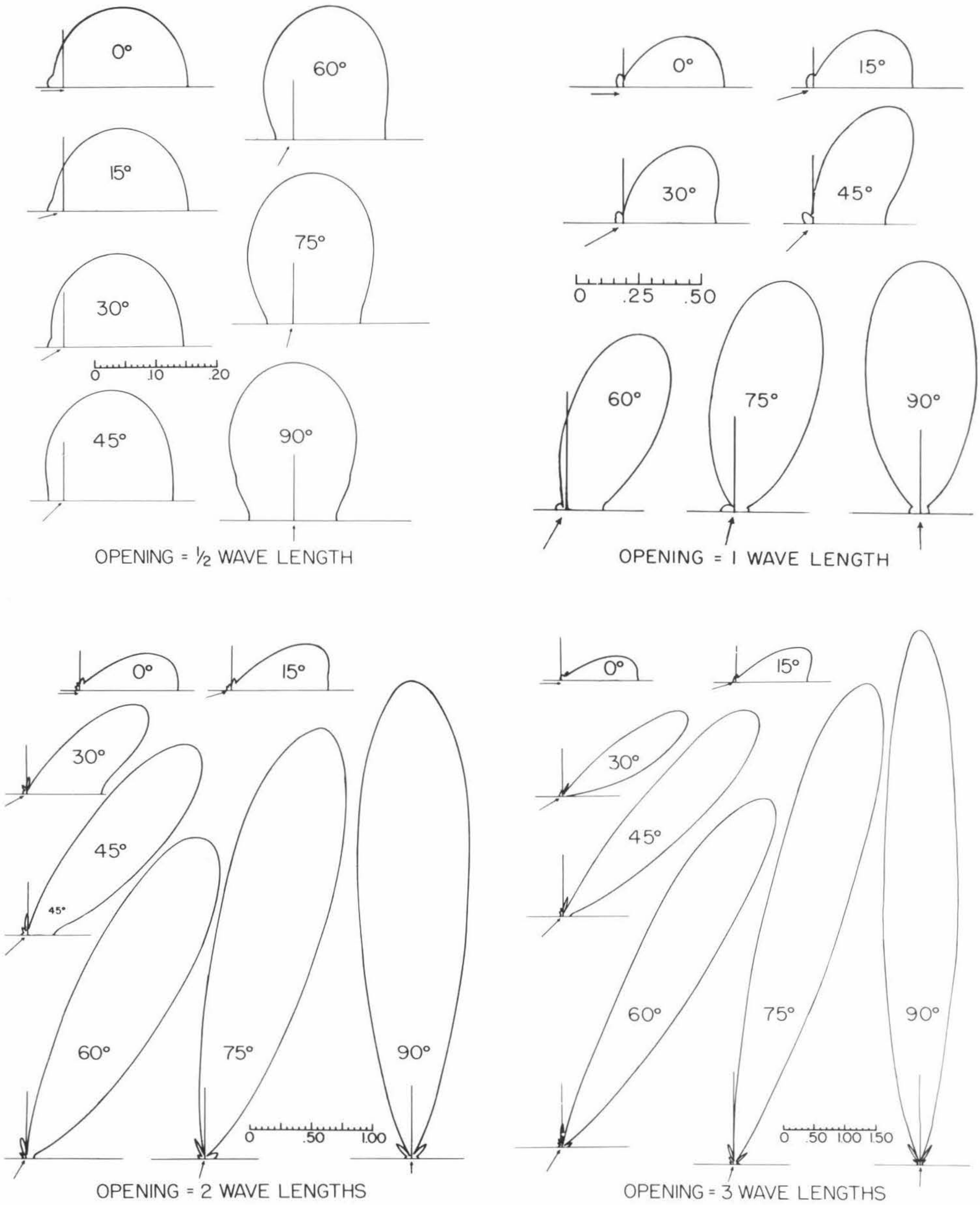


Fig. 5 - Polar Plots of Intensity Factors, $I_{R,\phi} = \frac{(h_{R,\phi})^2}{(h)^2} \times \frac{R}{\lambda}$

(From Morse-Rubenstein diffraction theory for vertical face straight breakwater)

For any given entrance conditions the diffraction pattern can be plotted as in Fig.6, showing the ratio of wave amplitude passing a location to the incident wave amplitude. Fig.6 is a schematic drawing and shows the alignment of wave crests at an instant. It extends to some arbitrary lower limit of wave height ratio, and gives some typical values for an oblique wave approach. The wave height ratio at any one location depends upon its distance from the opening, its angular orientation, the angle of wave approach, the width of the breakwater opening, and the incident wave length, but the ratio does not change with time after a steady state is reached. Fig.6 is the basis of the graphical solution. It can be considered as representing all of the energy which has entered through the breakwater opening during the time required for the furthermost wave crest to reach its arbitrary lower limit. All of this energy must be accounted for regardless of harbor size or shape. The problem, then, is to graphically redistribute the energy in the harbor correctly.

It can be shown that an incident wave reflected from a barrier may be treated as the mirror image of the extension of the incident wave as illustrated in Fig.7. Using this principle the wave crests of the diffraction pattern can be reflected from any barrier and superimposed on the incident wave. The diffraction pattern is "folded" along any barrier to achieve this mirror image superposition. The result of this "folding" is shown in Fig.8 for only the first reflection from each boundary of a square harbor. Careful

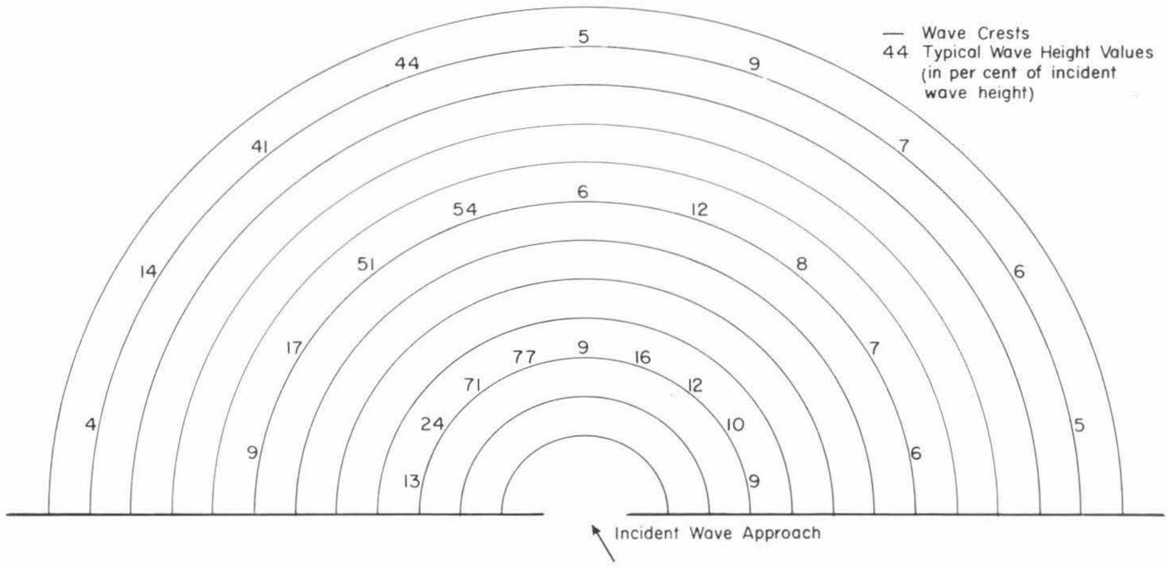


Fig. 6 - Idealized Wavecrest Diffraction Pattern Behind a Breakwater

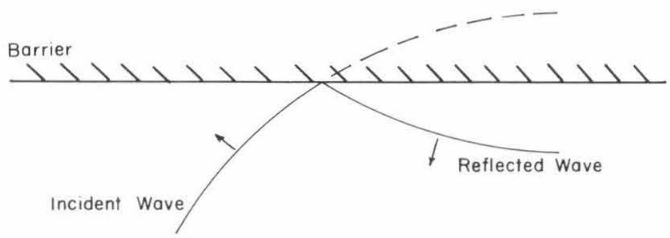


Fig. 7 - Reflection of a Wavecrest from a Straight Boundary

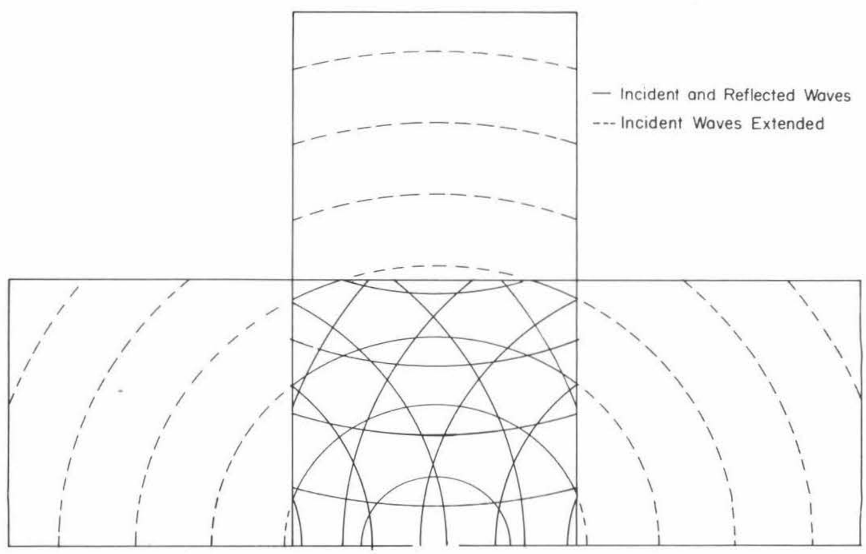


Fig. 8 - First Reflections in a Square Harbor

observation shows that this is the same as using mirror images of the harbor placed on the diffraction pattern. This latter method was used for ease of analysis and is explained in Section III B.

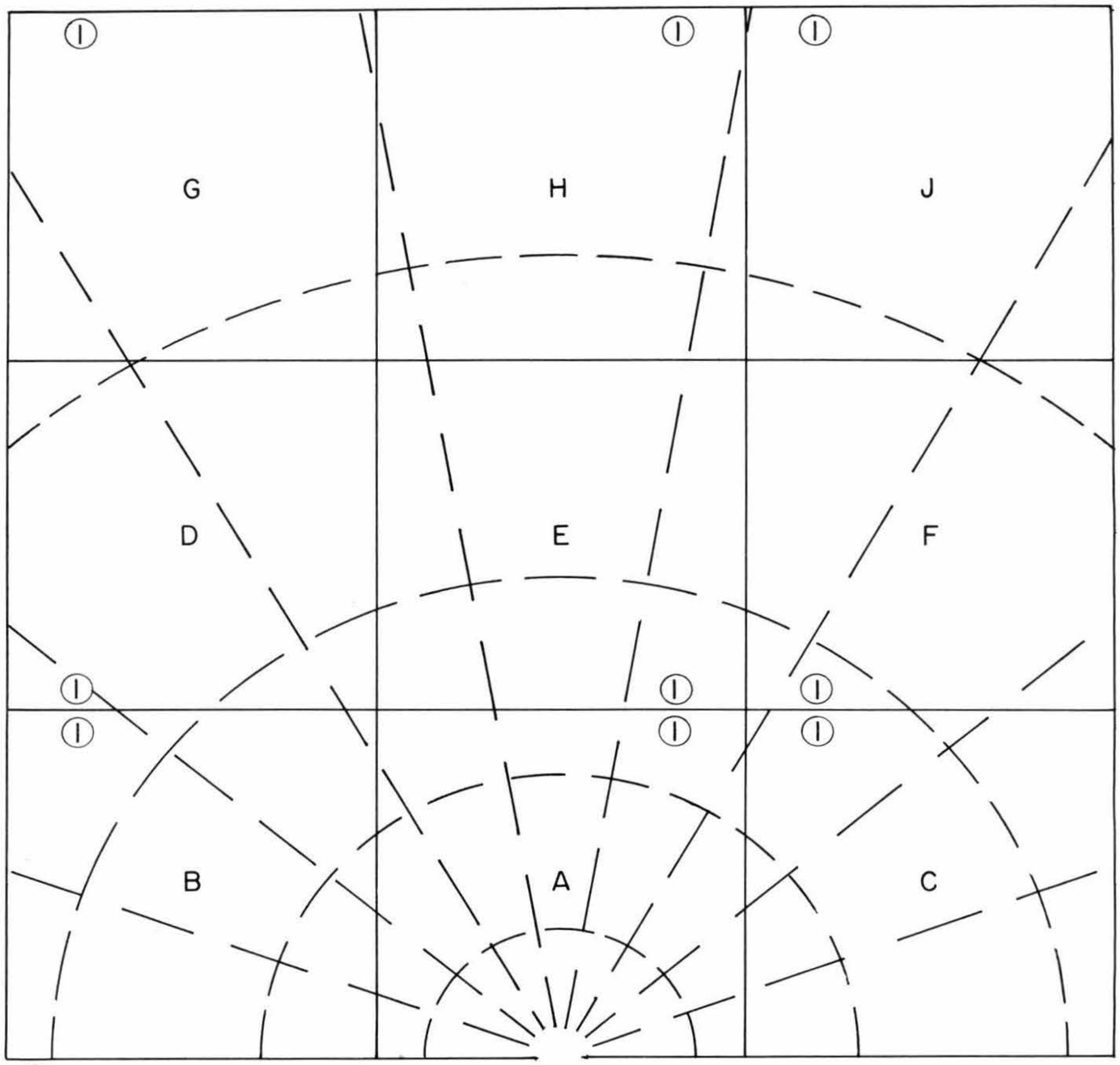
When the wave crests of the diffraction pattern are reflected by the above procedure, there exists at any location in the harbor the incident wave plus several reflected waves. The wave heights of these wave trains are known from the diffraction pattern, and by combination of these heights, the disturbance at any given location can be determined.

B. Graphical Procedure

1) Square harbor, constant depth, vertical bulkhead boundaries, no beaches.

The first step in the graphical solution is the construction of a diffraction pattern similar to Fig.6 as illustrated by the dotted portions of Fig.9. The difference between these figures is that in Fig.9 the pattern has been divided into areas of approximately equal wave amplitude, such that each ratio can represent a relatively large area without appreciable error.

A series of successive mirror images of the harbor to be studied, a square harbor in this case, are constructed as an overlay to the diffraction pattern. For any given entrance condition the value of the ratio in each area can be determined. The diffraction pattern and harbor outlines, of course, must be drawn to the same scale. The center of the breakwater opening is placed to coincide with the



1 Position within harbor

A-J Harbor and mirror images

Fig. 9 - Idealized Diffraction Pattern with a Square Harbor Overlay — No Beach

origin of the diffraction pattern. The square labelled A, Fig.9, is the harbor and the remaining squares are successive mirror images. Sufficient mirror images to cover the diffraction pattern are required, the pattern being bounded by some arbitrary lower limit of wave height ratio. It must be stated that, for the time being, the energy reflected out the breakwater opening is neglected.

The next step in the procedure is the determination of the disturbance at any particular location, such as position 1 in Fig.9. Position 1 occurs in the original harbor and each mirror image. For each square, position 1 occurs in a specific area of the diffraction pattern, for which the ratio is known. All of these areas will coincide after "folding" and their ratios are combined to determine the significant disturbance for position 1.

The method of combination is, of course, a vital part of the procedure. At any position there are wave trains travelling in many directions and the water surface will be choppy and confused. It is desired to determine the significant disturbance, as previously defined, at any position.

It was noticed in the model tests that a steady state was reached within a fairly short time after the wave machine was started. This means that after a short time the energy added to the model basin per unit time is exactly balanced by energy being removed from the system. Without any energy losses it would be expected that the waves in the basin would increase to infinite height. This, however, is not the case and, therefore, an attempt should be made to account for the energy losses.

The energy losses may be considered in four categories. First is the loss of energy reflected out through the breakwater opening. This, as previously stated, is neglected herein since it is believed small. Second is the loss of energy on the beaches and by imperfect reflection at the vertical harbor boundaries. Third is the loss due to bottom friction, and fourth is the loss of energy due to interference of wave trains. It is believed that the latter accounts for most of the energy loss in the system.

To approximately account for these losses in the graphical solution, all except the part due to the beaches are lumped in a "reflection factor" (taken empirically to be 85 per cent) applied to the vertical boundaries. Therefore, the wave height ratio for each area of the diffraction pattern was reduced depending upon the number of reflections. For example, the ratios in the areas of square A in Fig.9 were not reduced; the ratios in square B, E, and C were reduced to 85 per cent; the ratios in square D, H, and F to $(.85)^2$; etc. This device of a pseudo reflection factor gave good results in the present cases, and avoided the extreme complication of estimating the separate losses individually.

The ratios for position 1 were tabulated and reduced depending on the number of reflections. These ratios may now be called "adjusted values", and were combined to determine the significant disturbance for position 1.

The factor of 85% was used to obtain results comparable to the data for the specific models investigated. It should not be expected, however, that the same factor should be applicable to other conditions. It will be necessary to use other coefficients, of probably the same order of magnitude, for other harbors.

A further step necessary to obtain results comparable to the experimental data is the proper combination of the adjusted values. It was found that the summation of the three highest adjusted values for any position results in a value which is a direct function of the disturbance for the position. This function happens to be directly equal to the significant wave height as previously defined.

The summation of the highest three adjusted values is not entirely arbitrary for the following reason. Any three wave crests travelling in different directions in a location must intersect simultaneously at a point; more than three crests may intersect simultaneously but the probability of this occurring becomes increasingly small with a greater number of crests. Therefore, the summation of the three highest values should give a wave height which is near the maximum for a given area. It is reasonable to expect then, that the significant wave height bears some relationship to this near maximum. In this case it was equal.

It is seen that the method described is empirical with regard to the "reflection factor" and the use of only the highest three adjusted values. A graphical method such as this must necessarily be empirical. However, the results obtained appear to be reasonably good.

2) Square harbor, constant depth, vertical bulkhead boundaries, with a perfectly absorbing beach.

To analyze a harbor with an absorbing beach, a diffraction pattern with a harbor overlay is constructed similar to Fig.9. With an absorbing beach energy is dissipated and must be accounted for. Fig.10 was constructed with the beach drawn in the harbor and all mirror images. All the energy incident upon the beach is assumed to be completely dissipated, and this loss is accomplished graphically by deleting the diffraction pattern in the "shadow" of the beach in the harbor and all mirror images. This deletion is correct from a total energy standpoint, but is not correct from a distribution standpoint, because of diffraction into the "shadows". Althouth it is desirable to redistribute this energy, such redistribution becomes highly complicated. The method used, therefore, involves no redistribution.

After Fig.10 is constructed and the shaded portions are deleted, the determination of the disturbance at a position is carried out exactly as before. For position 1 the value of the ratios in all shaded portions is zero, and elsewhere adjusted values are calculated as before. The three highest adjusted values are added to determine the disturbance at the position in question. In this analysis the results obtained were again reasonably good, notwithstanding the fact that no energy redistribution in the "shadow" of the beaches was attempted.

The method of deleting shaded portions may be used to account for the energy reflected out through the breakwater opening, for the

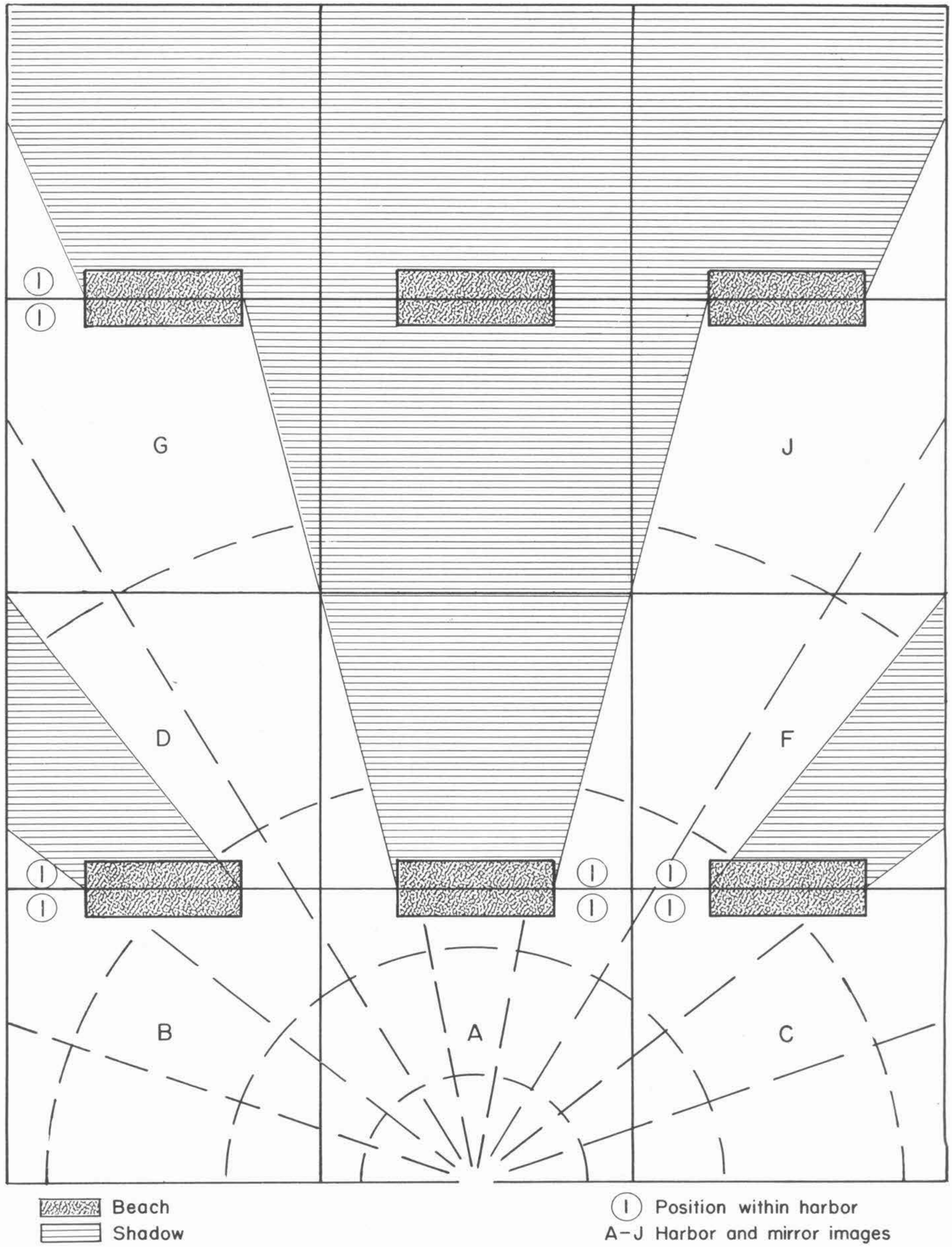


Fig. 10 - Idealized Diffraction Pattern with a Square Harbor Overlay — With a Beach

opening is similar to the perfectly absorbing beach in that each causes a loss in total energy within the harbor. The method used above for the square harbor with no beach may therefore be modified accordingly. The desirability of such modification will be discussed in Section III C.

C. Graphical Results and Conclusions

In Figs. 11 and 12 are shown the results of the graphical solutions as described above. The wave approaches, beaches, and positions are the same as used in the experimental tests except that more positions were used in the graphical method. The harbors with 750-ft beaches were not analyzed because the experimental results showed practically no difference between the values with a 750-ft beach and no beach, and similar results were expected in the graphical analysis.

Comparison of the graphical and experimental results is shown in Figs. 13a and b. These plots show the deviation of the graphical from the experimental expressed as a percentage of the latter. Fig. 13a shows all comparisons, while Fig. 13b excludes those comparisons with experimental values of 40 per cent or less of the wave height ratio. The effect of doing this is to show how well the graphical method holds for high and low values of experimental ratio.

Examination of Figs. 13a and b shows that the graphical method, in general, gives greater percentage deviations for low values of wave height ratios than for high values. Practically, however, this is

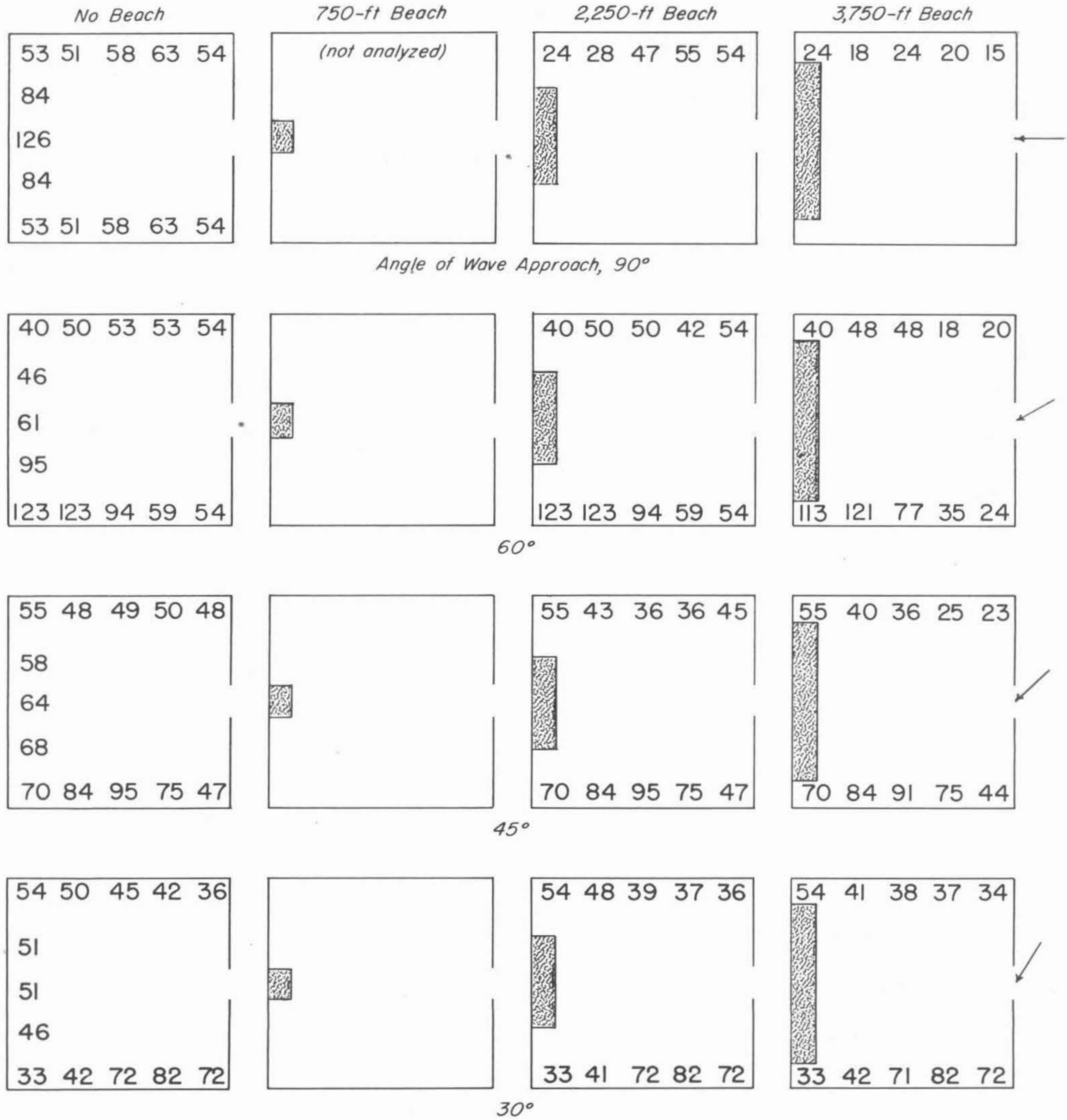


Fig. 11 - Computed Disturbance Factors for Square Harbors
Numbers refer to same areas as in Fig. 3

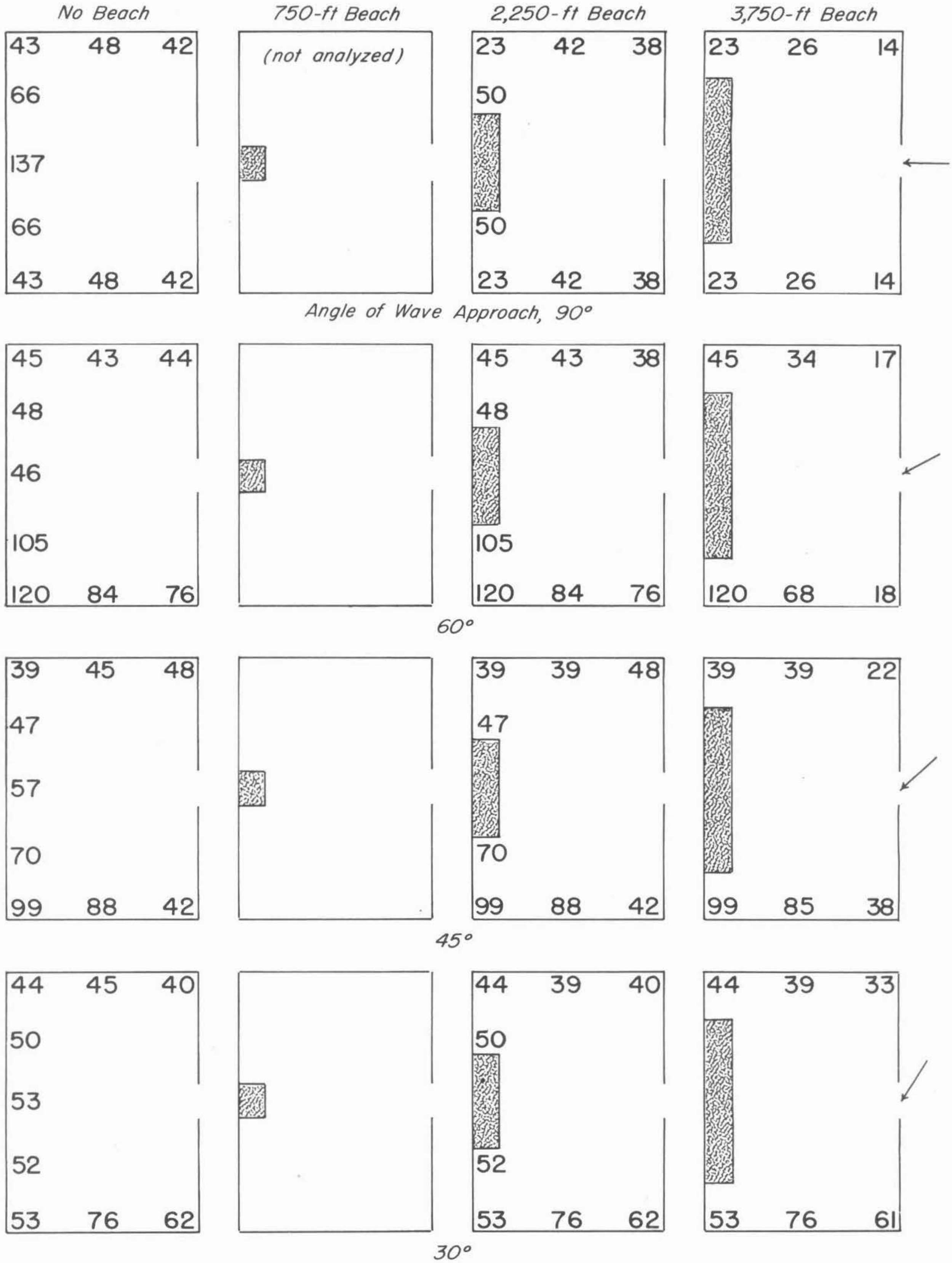


Fig. 12-Computed Disturbance Factors for Rectangular Harbors
Numbers refer to same areas as in Fig. 4

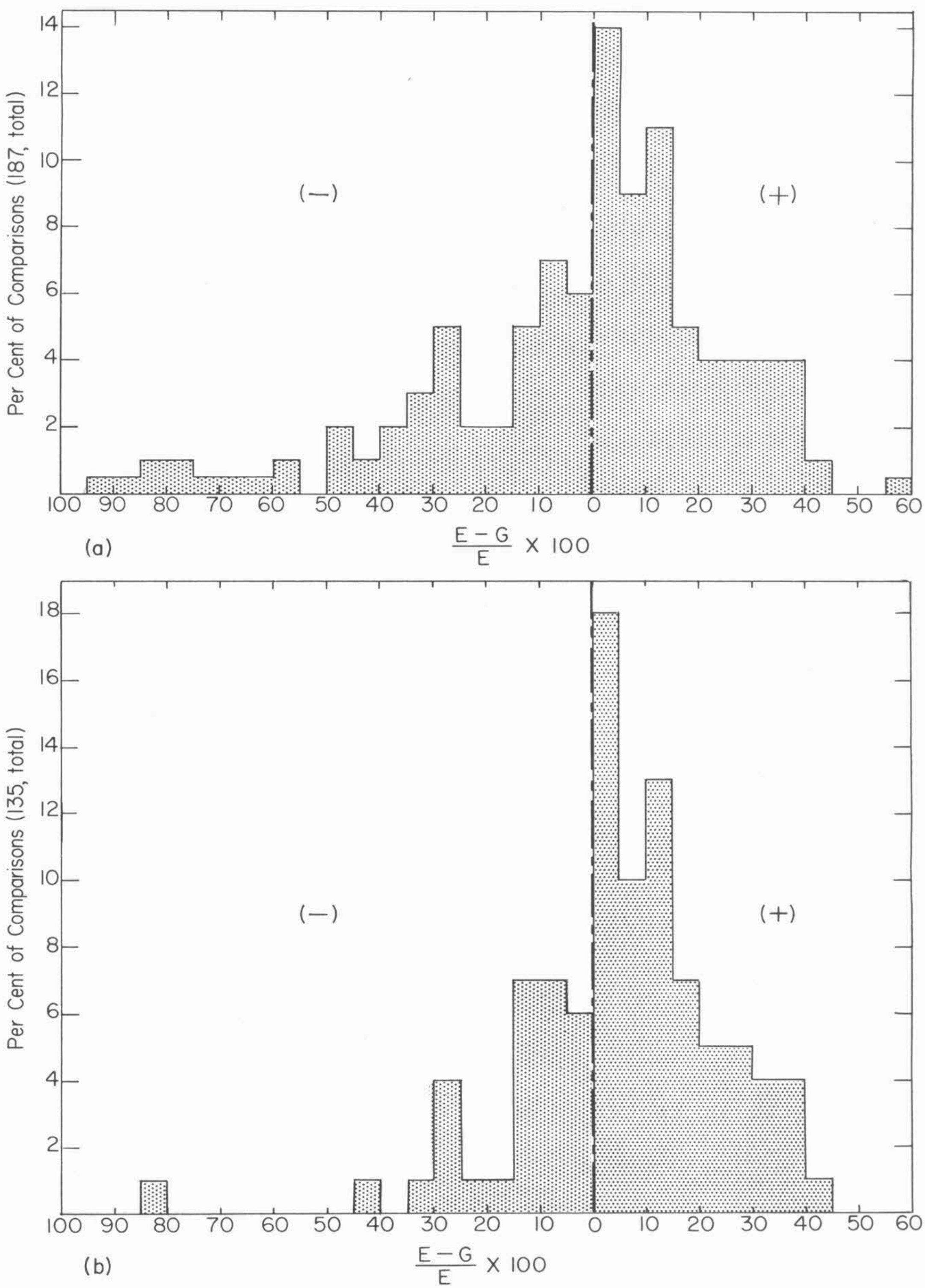


Fig. 13 - Comparison of Experimental and Graphical Results
(a) All data included (187 comparisons)
(b) All data for measured wave height ratio less than 40 per cent excluded

permissable since low values of wave height ratio usually result in waves that are not significant.

Excluding the lower values of experimental ratio, it appears then, that the correlation between the graphical and experimental results is reasonably good. The deviations are no doubt largely due to the approximations used in the graphical procedure and errors in the experimental techniques.

The loss of energy reflected back out of the breakwater opening was neglected in the graphical analysis because it appeared not to change the results. For openings greater than 2 wave lengths, however, it may be necessary to consider it.

The graphical method is a very rapid means for the determination of the wave disturbance conditions in a harbor. Only one diffraction pattern need be constructed for all analyses, the areas being designated by distance in wave lengths from the opening and by angular orientation. Values can be computed for all areas corresponding to various possible wave approach conditions and then arranged in tabular form. Such tabulation has been partially completed by this Laboratory. The harbor to be analyzed, with sufficient mirror images to cover the pattern, can then be drawn as an overlay. With this one setup all approach conditions can be analyzed and the disturbance throughout the harbor determined.

IV. SUMMARY

In rectangular harbors with the entrance in a long side, the peripheral wave disturbances, as measured by the significant wave height, are slightly less (14 per cent on the average) than in square harbors of the same area and with all other conditions equal.

The installation of the 750-ft beach does not affect the peripheral disturbance level in either harbor regardless of wave approach, while the disturbance decreases appreciably only with the 90° wave approach in the case of the 2250-ft beach. When the length of the beach is increased to 3750 feet a noticeable reduction in disturbance is accomplished for all wave approaches, being again most pronounced with the 90° approach.

While more energy enters any harbor with a 90° wave approach than with another approach, keeping the breakwater opening constant, the peripheral disturbance level with the experimental arrangement was found to be higher with the 60°, 45°, and 30° approaches than with the 90° approach, 72 per cent in the rectangular and 31 per cent in the square harbor. This result is entirely due to reflection.

A graphical method for determining wave disturbances in a harbor has been developed. The results obtained by this graphical method appear to be in relatively good agreement with those obtained by model tests. The method has been tested for square and rectangular harbors of constant depth, unaffected by currents, and having one breakwater opening. The boundaries may either be sloping or vertical. It may be possbile to extend the method to apply to harbors with other shapes and with more than one breakwater opening, but this has not yet been undertaken.

The method has not been proved for various wave lengths, various breakwater openings, or various incident wave heights, but should be applicable.

Tabulated values for the diffraction pattern can be computed using available data. Such tabulated values will allow the rapid determination (subject to the above limitations) of the disturbance conditions for any harbor, and for any wave approach condition.

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